Major controls on architecture, sequence stratigraphy and paleosols of middle Pleistocene continental sediments ("Qc Unit"), eastern central Italy

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Major controls on architecture, sequence stratigraphy and paleosols of middle Pleistocene continental sediments ("Qc Unit"), eastern central Italy

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Abstract

Middle Pleistocene continental sediments in central Italy ("Qc Unit") record the oldest fluvial accumulation along the uplifting margin of the Peri-Adriatic basin. The architecture of the sediment body can be divided into two unconformity-bounded, fining-upward cycles interpreted as genetically related depositional sequences. These sequences highlight the systematic adjustment of the fluvial system to changes in the ratio between accommodation space and sediment supply (A/S ratio) and, from base to top, comprise the following surfaces and stratal components: (i) a regionally correlative sequence boundary resulting from an A/S ratio ≤ 0; (ii) a low-accommodation systems tract characterized by conglomerate-rich, amalgamated channel fills and recording an A/S ratio < 1; (iii) an expansion surface marking the turnaround point from low-accommodation systems tract to high-accommodation systems tract deposits; (iv) a high-accommodation systems tract dominated by floodplain fines encasing lens-like, fluvial channel deposits and denoting an A/S ratio > 1; and (v) a mature red argillic paleosol. To constrain the climatic signal for paleosols formation, the two sequence-capping mature paleosols have been investigated. The results of these studies suggest that they were developed under humid and warm climatic conditions associated with interglacial phases, which have been correlatively attributed to Marine Oxygen Isotope Stages 11 and 9.

Keywords

MIS 11MIS 9Pleistocene paleosolsFluvial stratigraphyPedo-stratigraphy

Introduction

A frequent objective of the investigation of fluvial sedimentary successions is the study of the relative contribution of competing controls, such as tectonism, eustasy, climate change, and sediment supply, in shaping their stratigraphic record (e.g., Beilinson et al., 2013, Allen et al., 2013, Allen et al., 2014 Varela, in press). This is generally made possible in the Quaternary record (e.g., Browne and Naish, 2003, Amorosi et al., 2008, Püspöki et al., 2013.) by a series of favourable conditions including the availability of independently derived proxies for global sea-level history and climatic changes (e.g., Lisiecki and Raymo, 2005, Bertini, 2010).

Nonmarine strata of the middle Pleistocene "Qc Unit" exposed in southern Marche, eastern central Italy, provide an excellent opportunity to examine fluvial sediments deposited along an uplifting basin-margin setting during high-frequency sea-level changes. This unit has received only scant attention in the literature (Cantalamessa et al., 1986, Ori et al., 1991) and no architectural, sedimentological and paleopedological studies of the unit have hitherto been carried out.

The objectives of this paper are fourfold: (i) to provide a description and interpretation of the fluvial sedimentary facies identified in the outcrops of the Qc Unit in southern Marche; (ii) to better understand the large-scale stratigraphic architecture of this basin-margin succession by establishing a high-resolution sequence stratigraphic framework for its sedimentary record; (iii) to discuss the origin of the component sequences and their systems tracts in terms of interplay between regional uplift, glacioeustatic sea-level fluctuations, and climatically driven changes in the sediment supply regime; and (iv) to provide information about the paleoclimatic conditions in eastern central Italy during middle-Pleistocene interglacial periods using the paleosols present within the succession as climate proxies.

Geologic–geomorphologic setting and stratigraphy

The Plio-Pleistocene Peri-Adriatic basin is the youngest of a series of foreland basin systems developed from the Oligocene to the Neogene in front of the growing Apennine orogenic wedge during west-vergent subduction of the Adria Plate (e.g., Malinverno and Ryan, 1986, Doglioni, 1991, Argnani and Ricci-Lucchi, 2001). The Pleistocene tectono-sedimentary evolution of the central portion of the Peri-Adriatic basin is framed into a large-scale sequence-stratigraphic scheme (Cantalamessa et al., 1986). Specifically, within the traditional subdivision into Quaternary marine (Qm) and Quaternary continental (Qc) unconformity-bounded stratigraphic units, regionally correlatable unconformities divide the upper portion of the basin fill into three major allogroups (Qm1, Qm2, and Qc units, from oldest to youngest). The unconformities separating these units, which record phases of basin reorganization linked to the effects of long-term and regional-scale tectonics (e.g., Ori et al., 1991, Artoni, 2013, Bigi et al., 2013), are well recognizable along the basin margins and tend to become correlative conformities in a basinward direction. Allogroups record an overall regressive trend from slope and shelf mudstones of Qm1 (Cantalamessa et al., 2009, Di Celma et al., 2010, Di Celma et al., 2013, Di Celma et al., 2014, Di Celma et al., in press, Di Celma, 2011) through littoral sandstones and conglomerates of Qm2 (Cantalamessa and Di Celma, 2004) to conglomerate-dominated fluvial deposits (Qc). Since the end of the early Pleistocene, this portion of the Peri-Adriatic basin has experienced progressive uplift and a general tilting toward the east (e.g., Centamore and Nisio, 2003). An evaluation of uplift rates since the middle Pleistocene is constrained by the age and the distribution of Qm2 marine deposits, which have been uplifted up to 470 m above present sea level some kilometers inland of the coastline, providing a maximum value of about 0.5 m/ka over the last ~ 0.9 Ma. Long-term uplift rates after the middle Pliocene were higher along the central axis of the Apennines, where average uplift rates of 0.8–1.0 m/ka have been documented (Calamita et al., 1999, Coltorti and Pieruccini, 2000, D'Agostino et al., 2001, Centamore and Nisio, 2003). The middle Pleistocene regional uplift resulted in the formation of a laterally extensive angular unconformity that bevelled the top of the Qm2 Unit and marked the transition between the last marine episode recorded in outcrop in this part of the Peri-Adriatic basin and the establishment of fluvial depositional systems represented by the Qc Unit.

After the definitive emersion of the area, rivers started to incise within the former alluvial sediments creating a flight of four main alluvial terraces within the newly incised valleys (e.g., Coltorti and Farabollini, 2008, Farabollini et al., 2009, Wegmann and Pazzaglia, 2009, Calderoni et al., 2010). Based on morpho-, pedo- and litho-stratigraphy coupled also with archaeology, the terrace deposits of the Adriatic side of the Italian peninsula have been attributed to MIS 8, MIS 6, MIS 4–2 and MIS 1 (Coltorti and Pieruccini, 2006, Eppes et al., 2008).

Study area, methods and approaches

Study area

The study area stretches along the east coast of central Italy (Fig. 1A), between the towns of Torre di Palme in the north and Grottammare in the south and extends as far as 10 km inland (Figs. 1B and 1C). In this area, the fluvial strata of the Middle Pleistocene Qc Unit are exposed in a large number of gravel quarries and natural exposures between about 80 m and 480 m above present sea level. They form relatively wide and flat (typically 2°–3°), northeast dipping surfaces on the watersheds between east–northeast trending river valleys containing the aforementioned flight of four alluvial terraces (Figs. 1D, 2). Despite the poor age control on sediments of the Qc Unit, an estimate of their chronological setting is possible based on morphostratigraphy (the oldest and topographically highest fluvial terrace in the river valleys is attributed to the MIS 7) and the age of the immediately underlying Qm2 Unit in central Marche (900 ± 100 ka, Cyr and Granger, 2008), Emilia Romagna (MIS 21–19, Amorosi et al., 1998, Muttoni et al., 2011 or MIS 22–18, Gunderson et al., 2014) and Abruzzi (MIS 19–17, Agostini et al., 2007, Mazza and Bertini, 2013), which constrain the interval of Qc deposition to MIS 16–8. Equivalents of Qc Unit, displaying strong similarities in terms of both lithology and vertical stacking pattern of facies, have been identified along the Adriatic side of Italy in the Emilia (Amorosi et al., 2008), Abruzzi (Di Celma et al., 2000), and Molise (Bracone et al., 2012) Apennines.

Sedimentological field methods

In order to constrain the lateral and vertical distribution of individual facies associations in the Qc Unit, its stratigraphic architecture has been detailed through the use of a comprehensive outcrop-derived dataset including 1:10,000-scale geological mapping, line drawing over photographic panels, detailed description and interpretation of outcrops and extensive collection of paleocurrent readings. As described below, the nonmarine sedimentary succession has been subdivided into three facies associations. An individual facies association defines a particular depositional environment and comprises an array of physically and genetically related facies that are differentiated by grain size, bed configuration, lateral extent of beds or bedsets, bed thickness, grain sorting, and the presence or absence of primary sedimentary structures (all facies codes for fluvial deposits are from Miall, 1996). About 800 paleocurrent readings, obtained mainly from clast imbrications, channel margin trends and occasional cross-beds, provided the sediment dispersal pattern within the unit (Figs. 1B and 1C).

Paleosol investigation

The best exposures of three significant paleosol profiles (QcS1, QcS2 and QcS3), buried or relict, have been studied through macro-morphological description in the field following "classic" descriptive criteria (i.e., FAO, 2006). The studied paleosols belong to three different soil forming cycles that have strong pedo-stratigraphical meanings, due to their time-, climate- and environment-related features or association of features. In order to provide information about the degree of development in terms of climate- and time-related soil processes, the nature of these paleosols has been described by using the WRB (2006) soil nomenclature codes. Field observations and measurements have been integrated with undisturbed soil sampling for soil micromorphology, which has a high potential for qualitative or semi-quantitative observations about the changes of soil-forming processes through time and related environments and, therefore, past climatic, environmental and geomorphological dynamics (Kemp, 1985, Kemp, 1998, Catt, 1990, Fedoroff et al., 2010 and references therein). Thin sections were observed with a polarizing transmitted-light microscope and described following the terminology of Bullock et al. (1985) and Stoops (2003).

Sequence stratigraphic approach

In nonmarine sedimentary successions, when their relationship with coeval shoreline strata is impossible to establish, any reference to syndepositional shoreline shifts lacks the fundamental justification provided by the evidence of shoreline transgressions or regressions and the use of traditional systems tract nomenclature becomes inappropriate (Catuneanu, 2006). In this frame, owing to the lack of age-equivalent marine strata, the sequence-stratigraphic framework of the Qc Unit and its internal subdivision in sequences and component systems tracts have been described in terms of the changing ratio of the rate of accommodation space development and the rate of sediment supply (referred to as the A/S ratio), which define nonmarine stratigraphic units independently of marine base-level changes and associated shoreline shifts (e.g., Olsen et al., 1995, Martinsen et al., 1999, Plint et al., 2001). When the A/S ratio ≤ 0, there is no accommodation space at all; no accumulation occurs because of sediment bypass and regional erosion surfaces and/or sequence boundaries form. When 0 < A/S ratio < 1, sediment supply is greater than the available accommodation space, which is always filled by sediment. This situation leads to the formation of a low-accommodation systems tract (LAST). With an A/S ratio = 1, the balance between accommodation space and sediment supply results in an expanded surface with the formation of a systems tract boundary. When the A/S ratio > 1, the sediment is not able to fill all the available accommodation space and the probability of flooding on the alluvial plain increases. In this case, widely spaced channels and high preservation of fine materials occur, representing a high-accommodation systems tract (HAST).

Facies associations

Based on a variety of characteristics (primary sedimentary structures, bed thickness, texture, dominant grain size, internal bedding architecture, pedologenic features etc.), three main facies associations were differentiated within the studied succession. They reflect fluvial deposition (FA-A and FA-B) and soil formation (FA-C) in a large coastal plain setting. A detailed description and interpretation of the salient sedimentological features of the component sedimentary facies is given in Table 1.

Facies association A (FA-A)

Description

This facies association forms laterally extensive sheet-like conglomerate packages that are bounded at their base by composite erosion surfaces. These packages are invariably characterized by a dominance of clast-supported massive or crudely bedded conglomerate (facies Gh) with subordinate clast-supported planar cross-bedded conglomerate (facies Gp) and conglomerate channel-fills with concave-up bases (facies Gt) (Figs. 3A, 3B, 3C and 3D). Both extraformational and intraformational clasts are present. Extraformational clasts predominate and include varieties of chert, limestone, marl, calcarenite, and graywacke, all derived from the erosion of Late Jurassic to Pliocene formations exposed in the most internal portion of the Apenninic chain. Intraformational-clasts range from granule to boulder size and are formed by silty sand, silt and silty clay that could correspond to reworking of the adjacent floodplain sediments. Paleocurrent data derived from individual conglomerate packages invariably show wide dispersion.

Interpretation

The gravelly facies association represents a variety of channel-fill gravel beds (Gh and Gt) and bar forms (Gh and Gp) whose intimate association has many of the characteristics of fluvial gravels that are deposited in many ancient and modern braided river systems, as thoroughly described by many workers (e.g., Smith, 1974, Hein and Walker, 1977, Rust, 1978, Browne and Naish, 2003). The erosional bases and lenticular shapes in bodies of this facies association are consistent with deposition in shallow incised channels of low sinuosity that were up to 4 m deep and a few tens of meters wide. Overall, the coarse grain size of the channel fill sediments, the predominance of sediments recording downstream migration of gravelly longitudinal bars, the multi-story character of the deposit, the sheet-like external geometry of the conglomerate bodies, and the relatively low dispersion of paleocurrent data, indicate high energy discharge and prevailing bed-load transport within an extensive braid plain (McPherson et al., 1987) in which a shifting network of unstable, low sinuosity, shallow channels were able to freely migrate laterally within a well-defined channel-belt (Kraus, 1984, Rust, 1984).

Facies association B (FA-B)

Description

This facies association is dominated by a monotonous succession of horizontally-bedded, bioturbated, rooted and pedogenically modified mudstones (facies Fl), with subordinate sand intercalations with a characteristic yellowish colour (facies Fm) (Figs. 3E and Fig. 3F). It occurs in continuous successions of several meters interfingering with or, more commonly, conformably overlying conglomerates of FA-A.

Interpretation

On the basis of fine grain size, sheet-like geometry, lack of channelization, and occasional occurrence of weakly developed paleosols, freshwater molluscs, and root traces, these strata are interpreted to represent deposition of suspended sediment from non-channelized flow across low-relief floodplains during flood stages. When flooding occurs, sediment-laden water drops relatively coarse-grained overbank sediments (fine sand and silt) near the channel whereas fine-grained sediments (clay) are transported into the flood basin. As a consequence, the coarser-grained portion of this assemblage (facies Fl) represents a more proximal floodplain setting with natural levee and crevasse splay deposits, whereas the clay-dominated part (facies Fm) indicates deposition from standing water or low-energy flows away from the main channel. The low maturity of the buried paleosols indicates short-living soil formation processes after or during deposition and that overbank floods were episodic (Kraus, 1999) with very low rates of sedimentation.

Facies association C (FA-C)

The study of paleosols by means of micromorphology allows the recognition of pedofeatures related to in situ processes of the past, their superimposition, the presence of monogenetic or polygenetic/polycyclic processes and, therefore, the reconstruction of the paleosols evolution through time (Fedoroff et al., 2010 and references therein), which in most cases also includes paleoclimatic and paleoenvironmental signals.

Here we describe three paleosol profiles (QcS1, QcS2 and QcS3) that were measured from three separate exposures of the Qc Unit. Their salient macroscopic features are summarized in Table 2. Field observations and micromorphological studies revealed that QcS1 is the less developed whereas QcS2 and QcS3 are strongly weathered and they represent pedo-stratigraphic markers traceable across the Peri-Adriatic region (i.e., Abruzzi and Molise, Di Celma et al., 2000, Bracone et al., 2012).

Paleosol QcS1

This brownish yellow buried paleosol is up to 1 m in thickness (Figs. 4A and 4B) and its parent material consists of finely laminated or massive calcareous sand and silt (FA-B). This paleosol has been investigated for its stratigraphic position, similar in the field to that of QcS2, and therefore its characteristics are crucial to assess its stratigraphic and environmental meaning. Also in this case the paleosol is truncated, eroded (locally by scours and small channels) and buried under coarse-grained gravelly deposits belonging to the FA-A. Although this paleosol can be followed in field for some tens of meters it is laterally discontinuous and in a few meters it disappears due to the deepening of the upper erosional surface and the upper gravels lay directly on the underlying fines. It can be seen as a pedofacies (Kraus, 1999) within the alluvial succession and therefore useful to determine the geomorphological and sedimentary dynamics during the depositional history.

Soil micromorphology

The coarse fraction is made of abundant poorly sorted (silt to coarse sand sized) unweathered monomineral granules of quartz and flint fragments, common slightly weathered muscovite, pyroxenes and amphiboles single mineral grains and carbonatic rock fragments (Fig. 5A). Quartz is about the 70% of the total coarse fraction. The mineral grains and rock fragments are angular to subrounded. The c/f ratio is 1/4 and the groundmass is made of an opaque dotted colloidal mass made primarily of micrite finely mixed with clays moderately impregnated by reddish brown to dark brown Fe hydroxides and oxides (Fig. 5A). The porosity is moderate and made of rounded biological voids and channels; rare cracks are also present. The dominant microstructure is massive with a typical calcitic cristallitic b-fabric, a subordinate weakly developed striated and porphiric related distribution.

Calcium carbonate precipitation pedofeatures are the most abundant. Calcite crystalline pedofeatures segregated into large disorthic nodules, coatings and infillings (Fig. 5B) are distributed throughout the Btk horizon. Two main phases of calcite precipitation are recorded: a first phase characterized by finely laminated calcite hypocoatings mixed with clay (Fig. 5B) that form also very thin dusty coatings around voids and granules or nodules; and a second phase made of void infillings of massive micrite impregnated by reddish brown ferruginous segregations (Fig. 5B).

In a few cases the last phase of illuviation is of detrital origin (Fig. 6C). In the same horizon Fe/Mn nodules are also common (Fig. 5A). The deeper Bk horizon is quite homogeneous and characterized by diffuse dusty dark micritic impregnation of the groundmass with rare nodules and sparitic and macrosparitic hypo-coatings around the voids (Fig. 5D).

Interpretation

The main information about the length of duration of the stability phase that allowed the soil formation is given by the absent or moderate weathering of primary minerals and the incomplete leaching of the carbonatic rock fragments belonging to the parent material (Fig. 5A). Primary carbonate leaching is primarily linked to the length of time available for the process and the amount of water that is mainly a function of the climate being equal to other factors that can play an important role at local scale. Therefore, QcS1 suggests a short-lived episode of surface stability and non-deposition on the valley floors supported also by the moderate accumulation of Fe oxides and hydroxides and related weak rubification. Pedogenic calcium carbonate precipitation occurred throughout the soil profile forming a calcic horizon that typically develops under climate with moisture deficit where complete carbonate leaching is prevented by the short duration or limited amount of moisture available during the wet season (Wright, 2007). The presence of two phases of strongly impregnating CaCO3 precipitation together with hydromorphic features suggests fluctuating water tables (Kelly et al., 2000, Wright, 2007) in arid and semi-arid climates (Birkeland, 1999, Royer, 1999, Retallack, 2000). However, some clay neoformation occurred as indicated by the groundmass and the subordinate striated b-fabric that also indicates shrinking and swelling processes related to seasonal contrast (Hussein and Adey, 1998, Kovda and Mermut, 2010). A scarcely stable surface is also revealed by the dusty and silty sandy micritic coatings. The overall characteristics of this paleosol can allow its tentative classification as Calcic Luvisol (WRB, 2006; sol brun fersiallitique, sensu Duchaufour, 1995). Therefore, the described features point to an early stage of soil formation phase under semiarid climatic conditions that can be correlated to interstadial periods already recognized in Quaternary alluvial successions of central-southern Italy (Scarciglia et al., 2003, Coltorti and Pieruccini, 2006, Zembo et al., 2012).

Paleosol QcS2

This reddish and strongly weathered buried paleosol is up to 2 m in thickness (Figs. 4C and 4D). The parent material is made of calcareous and cherty gravels and coarse to medium sands and silts (FA-A). Locally, the paleosol is also found on top of the gravels (FA-A). The upper part of the paleosol is truncated and buried under gravelly deposits belonging to the FA-A and the surface horizons are eroded. Rubified and strongly leached Bt horizons are the peculiar horizons that characterize this paleosol together with the presence of a deep moderately to strongly indurated Ck horizon. QcS2 can be considered as a distinctive facies or pedofacies (sensu Kraus, 1999) and its stratigraphic position allows a correlation with paleosol S2 of Bracone et al. (2012).

Soil micromorphology

The Bt1 and Bt2 horizons have very similar micromorphological features. The coarse fraction is solely made of poorly sorted (silt to coarse sand sized) monomineral granules of quartz (about 90% of the total), flint fragments and very rare muscovite needles (Fig. 5E). The granules are angular to subrounded and show a high degree of weathering (Fig. 5E); no primary carbonatic rock fragments or granules are left. The c/f ratio is 3/7 and the silty clayey groundmass is iron stained (reddish brown), dotted, with porphyric and subordinate striated b-fabric (Fig. 5E). The porosity is scarce, with very few cracks and rare rounded biological voids; the microstructure is massive to subordinated weak subangular blocky. The most common pedofeatures are Fe/Mn orthic and anorthic nodules and impregnation features scattered all over the mass rarely coupled with paler depleted areas (Fig. 5F). Microlaminated reddish clay coatings are rare and most of them are progressively assimilated into the groundmass (Fig. 5G). Only in the lowermost part of the Bt2 horizon are rare pedofeatures related to secondary pedogenic carbonate precipitation present. They impregnate the groundmass and are represented mainly by micritic and microsparitic hypo-coatings (Fig. 5H) and orthic nodules with diffuse boundaries.

Interpretation

QcS2 reveals the strong weathering of the primary minerals and the complete leaching of the primary carbonates. The result is the formation of well-developed rubified argillic horizons with Fe (hydro)oxides finely mixed with illuvial clays strongly assimilated into the groundmass. The presence of only one generation of clay coatings and the absence of other coarse-grained illuvial textural pedofeatures suggest a monogenetic nature for the paleosol. The common Fe/Mn and the rare depletion features are related to the low permeability of the deep argillic horizons and the presence of an intermittent fluctuating water-saturated environment occurring on the flat valley floor (Lindbo et al., 2010). The red colour is usually associated with rubification processes and commonly interpreted as occurring during interglacial conditions (Cremaschi and Trombino, 1998, Scarciglia et al., 2003, Scarciglia et al., 2006, Coltorti and Pieruccini, 2006) although red soils might also derive the colour from the colluviation of older red soils (Coltorti and Pieruccini, 2006). The lack of colluvial features and the monogenic evidence for its formation point out that the iron compounds (poorly crystalline ferrihydrites or very fine-grained hematite) were released in situ after severe weathering of the primary minerals during a single pedogenetic phase (Fedoroff, 1997, Yaalon, 1997). The single phase illuvial clay horizons, the reddish colour, the complete carbonate leaching and the strong weathering of the primary minerals are properties that indicate long-term geomorphologic stability of the surface and warm and humid seasonally contrasted climatic conditions typical of interglacials. The strong carbonate accumulation at depth can be associated with the downward flux of pedogenic carbonates during leaching and/or to fresh carbonate accumulation at the surface at the onset of unstable surface conditions possibly at the end of the fully interglacial conditions (Coltorti and Pieruccini, 2006). QcS2 paleosol can be described as a Chromic Luvisol (WRB, 2006), Fersiallitic soil of Duchaufour, 1992, Duchaufour, 1995, Red Mediterranean soil (Dudal et al., 1966) or Buried Truncated Leached Paleoeldisols (Nettleton et al., 2000).

Paleosol QcS3

QcS3 developed on top of the Qc Unit and, therefore, is found on the topographic surface at regional scale although its preservation is variable due to younger erosional processes and anthropic works (Figs. 4E and 4F). It is a relict paleosol and its formation spans back to the end of the deposition of the Qc Unit and continues through time under different environmental conditions than those of today. Therefore it also assumes the significance of polygenetic soil, or vetusol, since its evolution is linked to the different environments that occurred during the middle-late Quaternary (Cremaschi, 1987, Bronger and Catt, 1989). The stratigraphic position of this paleosol allows its correlation to the paleosol S3 of Bracone et al. (2012). The described profile is up to about 3 m in thickness with a wavy, abrupt lower boundary toward the underlying floodplain calcareous gravelly and sandy deposits that are the parent material. This paleosol is well-structured with a dominantly clayey texture and is intensely rubified although with reddish-brown and orange mottles due to hydromorphic processes. It is characterized by a sequence of strongly weathered and leached Bt horizons with secondary carbonate precipitation that indicates the supply at the surface of fresh carbonate sediments after the complete leaching of those belonging to the parent material. The deeper calcic horizons are thick and locally hardly cemented.

Soil micromorphology

The coarse fraction is strongly weathered, the carbonatic fraction of the parent material completely leached and only quartz monomineral granules and flinty fragments are left. Physical and chemical weathering is usually very strong and mainly represented by clay neogenesis, Fe-oxides staining and Fe/Mn coatings (Fig. 5I). Very rare small and strongly weathered muscovite is also present.

The microstructure is a well-developed subangular blocky mainly made of cracks and planar voids. The groundmass is an opaque, dotted mix of clays and Fe/Mn stainings. The more significant and abundant textural pedofeatures are represented by clay coatings, which are very abundant throughout the argillic horizons. Different generations of clay coatings can be recognized. The older is dark reddish and characterized by a strong assimilation of clay pedofeatures within the soil matrix with sharp extinction bands under XPL (Fig. 5J). Rounded clay pedorelicts are also present mixed within the groundmass. A further generation is made of impure, strongly Fe/MN impregnated and weakly laminated dark reddish to orange reddish clay infillings, also characterized by the presence of silty mixed mineral grains (mainly quartz). The youngest generation of clay pedofeatures, yellowish orange to yellowish red in color, is mainly found as coatings and infillings within planar horizontal voids and at minor extent biological voids (Fig. 5K). They are dominantly pure and weakly laminated and characterized by thin blackish Fe/Mn hypocoatings and quasicoatings. This final generation of clay pedofeatures is also younger than the calcium carbonate precipitation features that affect the whole soil profile (Fig. 5L). Calcium carbonate precipitation features are scattered throughout the profile although more abundant in the Btk1 and Btk2 horizons. They are typically dark, opaque micritic impregnations, nodules and hypocoatings followed and usually surrounded by irregularly distributed sparitic and macrosparitic impregnations and hypocoatings (Fig. 5L). These last pedofeatures disturb and disrupt the groundmass also incorporating residuum of the original soil material. Redox pedofeatures are common although more abundant in the Btgk horizon where paler colours are dominant and represented by impregnative Fe/Mn features such as hypocoatings and nodules together with depletion features (Fig. 5K).

Interpretation

After the end of the deposition of Qc2 the topographic surface underwent to stability and soil forming processes. This surface became an alluvial terrace following the valley downcutting and became a relict surface until present-day. The QcS3 paleosol is characterized by the following main soil forming processes: a) strong weathering of primary minerals and complete leaching of primary carbonates; b) more than one phase of clay neoformation, and illuviation (formation of deep Bt horizons); c) rubification; d) accumulation of carbonates in deep calcic/petrocalcic horizons; e) precipitation of secondary pedogenic carbonates throughout all the preserved horizons; f) colluvial processes and re-working of soil particles; and g) hydromorphic features formation. The first four processes indicate long-lasting and repeated phases of geomorphologic stability under dense vegetation cover and warm and wet climatic conditions. The presence of more than one generation of clay illuviation features suggests polycyclic and polygenetic processes through different interglacial periods (Cremaschi, 1987, Coltorti and Pieruccini, 2006, Zembo et al., 2012). The precipitation of secondary carbonates following the primary carbonate leaching and the colluvial features indicate the disturbance of the topographic surface and the onset of erosional and depositional processes (fresh carbonates) leading to the retrogradation of the soil properties possibly related to the decline of the vegetation cover. This occurred due to the repeated shifting toward cooler stadial conditions, the onset of colluvial and/or runoff processes and the erosion of the former soil cover. In particular, the deposition of the youngest generation of clay illuviation features juxtaposed on the secondary carbonate features points out repeated wet and warm against arid and cool climatic conditions and related geomorphological stability and unstability phases of the topographic surface typical of several alternating interglacial and glacial stages (Coltorti and Pieruccini, 2006, Scarciglia et al., 2006). Moreover, the presence of common horizontal planar voids throughout the profile and their coating or partial infilling by the younger generation of clay coatings suggests frost activity within the soil related to the alternating cool conditions during the glacial stages (Van Vliet-Lanoe, 2010 and references therein). Despite its polycyclic character also this paleosol can be classified as Chromic Luvisol (WRB, 2006).

Discussion

Facies architecture and sequence stratigraphy

The overall sediment body architecture of the Qc Unit can be resolved into two unconformity-bounded cycles (Qc1 and Qc2) that can be interpreted as genetically related depositional sequences (Fig. 3a). These sequences occur as fining-upward fluvial successions that are weathered on top by mature paleosols or are erosively overlain by the coarser grained base of the succeeding sequence without an intervening paleosol. Changes in A/S ratio result in systematic changes in the relative proportion of channel fills and floodplain deposits and allow the subdivision of the nonmarine depositional sequences into low- and high-accommodation systems tracts (e.g., Catuneanu, 2006, Beilinson et al., 2013, Foix et al., 2013). A similar stratigraphic packaging, forms the basic motif of the middle-late Quaternary deposits from central Po Plain (Amorosi and Colalongo, 2005, Amorosi et al., 2008) and Molise region (Bracone et al., 2012).

Channel-dominated, low-accommodation systems tract (LAST)

Low-accommodation systems tracts typically form on top of subaerial unconformities, reflecting periods of relatively low (smaller than unity) A/S ratio (Fig. 6A). During these stages of renewed sediment accumulation within a nonmarine setting, fluvial channels can aggrade only minimally and are forced to shift laterally, causing both regional scouring of a smooth sequence bounding unconformity and deposition of a sheet conglomerate reflecting an extended phase of channel reworking and minimal vertical channel stacking (e.g., Gibling and Bird, 1994, Olsen et al., 1995, Sønderholm and Tirsgaard, 1998, Takano and Waseda, 2003, Allen and Fielding, 2007). Fine-grained floodplain deposits may also develop at this stage but, due to erosion by lateral channel migration, they have a low probability of preservation.

Across the entire study area, sequences Qc1 and Qc2 at the base are largely dominated by laterally amalgamated channel conglomerates (FA-A) deposited in braided river systems, whereas fine-grained floodplain deposits (FA-B) are restricted to locally preserved erosional remnants that rarely exceed more than a few tens of meters laterally. The facies associations and distribution suggest the deposition in the distal portion of an unconfined, coalescent alluvial fans system that emanated from the adjacent Apennines fold-thrust belt. The prevalence of multistorey braided channel bodies and conspicuous dearth of preserved floodplain sediments indicate relatively low aggradation rate conditions and a relatively high amount of sediment supply, suggesting that the conglomerate-dominated intervals at the base of sequences Qc1 and Qc2 formed under low A/S ratio conditions. These conditions occurred typically during glacial stages when little new accommodation space is added to the fluvial profile due to the sea-level lowstand and high sediment supply is provided by the erosion of the slopes under cold and arid conditions (e.g., Coltorti and Pieruccini, 2006). Accordingly, these amalgamated channel-fills and, where preserved, their laterally adjacent floodplain sediments are interpreted as low-accommodation systems tract (LAST) deposits characteristic of initial stratigraphic base-level rise. Given the overall unincised nature of the sequence boundaries at the base of this systems tract (namely, SU1 and SU2), it is suggested that during periods of lowered base level the fluvial system prograded over a vast area of an emergent, gently sloping shelf (e.g., Woolfe et al., 1998, Posamentier, 2001).

Expansion surface (ES)

In fluvial sequences, the progression from low- to high-accommodation conditions commonly occurs across a surface or zone recording an abrupt or gradual increase of the A/S ratio and characterized by a conformable vertical transition from laterally amalgamated, channel-filling conglomerates to fine-grained floodplain deposits (Fig. 6B). This surface, or zone, denoting an important change in fluvial style, is termed an expansion surface by Martinsen et al. (1999) and has been commonly interpreted as the nonmarine correlative of the maximum regression surface (e.g., Rogers, 1998, Amorosi and Colalongo, 2005).

Within Qc sequences the vertical transition from a tabular, amalgamated, braided fluvial channel belt with high channel/floodplain ratio to a fine-grained floodplain facies association with low channel/floodplain ratio occurs across a conspicuous lithological contact (Fig. 7). This contact, reflecting a major change in the stratigraphic architecture, is interpreted to mark the turnaround point from low-accommodation systems tract (LAST) to high-accommodation systems tract (HAST) deposits.

Floodplain-dominated, high-accommodation systems tract (HAST)

High-accommodation systems tracts (HASTs) record periods of A/S ratio greater than unity (Fig. 6C). In such a circumstance, the progressive increase in accommodation space relative to sediment supply provides an ideal condition for rapid aggradation and preservation of widespread floodplain deposits (Wright and Marriott, 1993, Takano and Waseda, 2003). Streams are in a constant state of avulsion producing ribbon-like channel bodies encased in a fine-grained floodplain facies association that makes up the bulk of the HAST.

Given the positive correlation existing between aggradation rate and preservation of floodplain deposits (e.g., Bridge and Mackey, 1993), the upward increase in the proportion of floodplain strata documented in the studied sequences is suggestive of relatively high aggradation rates in response to a rapid increase of the A/S ratio. Accordingly, the laterally extensive, overbank-dominated packages overlying the conglomerate-rich LASTs have been classified as HASTs.

Nonmarine sequence boundary

One of the keys to interpreting the architectural assemblages related to alluvial depositional sequences is recognizing sequence-bounding unconformities of regional extent. In nonmarine settings, sequence-bounding unconformities record zero to negative A/S ratio and are usually defined as widespread surfaces of non-deposition and subaerial erosion associated with an abrupt shift in the channel-overbank ratio and presence of mature and laterally extensive paleosols (e.g., Wright and Marriott, 1993, Shanley and McCabe, 1994, Aitken and Flint, 1995, McCarthy and Plint, 1998, McCarthy et al., 1999, Plint et al., 2001 among others). Sequence boundaries are placed at the top of the paleosol units because the paleosol's top represents the end of a terrestrial event, that is, a hiatus in sedimentation and the modification of a depositional surface by pedogenesis.

Within the Qc Unit, sequence boundaries are regionally correlative subaerial unconformities picked at the base of laterally extensive, amalgamated fluvial-channel bodies (FA-A) and recording significant interruptions in basin depositional history. Three such prominent discontinuities, labelled SU1–3 in ascending order, are recognized in the Qc Unit. They largely conform to the standard definition of a nonmarine sequence boundary, showing evidence of erosion and/or prolonged subaerial exposure (mature paleosol development) and an abrupt increase in sediment grain size with respect to the underlying strata. As such, the sequence boundaries within the Qc Unit are similar to other interpreted sequence boundaries in alluvial strata (e.g., Gibling and Bird, 1994, Shanley and McCabe, 1994, Olsen et al., 1995, Allen and Fielding, 2007), where there is a sharp juxtaposition of braided fluvial-channel fill deposits over floodplain deposits marking a prominent reduction of the A/S ratio.

Contact between units Qm2 and Qc (SU1)

The unit-bounding fluvial unconformity at the base of Qc is a regionally distinctive erosional surface (surface SU1) that bevels the underlying Qm2 shallow-marine deposits and records an abrupt basinward shift in depositional environment and a significant gap in the stratigraphic record. At a regional scale, this contact is a relatively smooth, gently eastward-dipping, broadly spoon-shaped surface; on the outcrop scale, it shows variable erosional relief on underlying strata, typically less than 5 m (Fig. 8A), although evidence of developed incised valleys is lacking. Judging from the systematic absence of unambiguous evidence for pedogenic alteration, SU1 is interpreted to record regional planation of underlying marine strata by pronounced fluvial scouring.

Contact between Qc1 and Qc2 (SU2)

The intra-unit sequence boundary separating Qc1 and Qc2 (surface SU2) is a regionally significant contact marking an abrupt change from high- to low-accommodation conditions as well as a major shift in the channel-floodplain ratio. At a regional scale, this surface is a very low-angle, eastward-dipping angular unconformity. Besides the local relief provided by conglomerate-filled shallow scours and steep-sided cuts, generally less than 4 m deep, there is little evidence that the unconformity has significant relief on a larger scale.

Depending upon locations, this boundary has different outcrop characteristics. At relatively seaward locations, adjacent to the present shoreline, the SU2 sequence boundary truncates a laterally discontinuous reddish, mature paleosol (QcS2), whose characteristics point out long lasting geomorphological stability, subaerial exposure of the floodplain and incision of the fluvial channels associated with warm and wet climatic conditions under dense vegetation cover typical of fully interglacial conditions (Fig. 8B). Breaks in the lateral continuity of this paleosol occur where the surface incised through the underlying Qc1 sediments during the initial deposition of the new sequence (Figs. 8C, 8D, and 8E). Landward, in the direction of higher uplift rates, the SU1 and SU2 sequence boundaries converge and the QcS2 paleosol becomes progressively rarer and eventually disappears.

Exposure surface at the top of Qc2 (SU3)

The Qc2 sequence is capped by the QcS3 paleosol, a polycyclic and polygenetic paleosol which characterizes the modern topographic surface (SU3). The paleosol features point out repeated cycles of soil formation and retrogradation through alternating warm/wet and cool/arid climatic conditions typical of interglacial and glacial stages. This occurred since the topographic surface became a relict surface after the incision of the river valleys and SU3 therefore corresponds to the composite basal erosional surfaces of the alluvial terraces found within the present day fluvial valleys.

Sequence-forming mechanism

In recent studies it is widely held that fluvial systems respond to relative sea-level changes and the resulting shifts in shoreline position only within a limited distance upstream from the coeval shoreline and that this distance, which may vary greatly with the gradient of the alluvial plain and the discharge of the river, ranges from several tens to a few hundreds of kilometers (i.e., Schumm, 1993, Leeder and Stewart, 1996, Blum and Törnqvist, 2000, Holbrook, 2006, Hampson et al., 2012). Beyond this point, the upstream influence of sea-level fluctuations is likely to be limited and other factors, such as climate, discharge, and local tectonism, are thought to become increasingly important controlling factors on fluvial architecture (e.g., Shanley and McCabe, 1994, Holbrook and Schumm, 1999, Martinsen et al., 1999).

Assuming that during the middle Pleistocene the shelf offshore southern Marche was similar to the modern shelf setting, the studied succession was deposited some 40 km west of the lowstand shoreline and just a few kilometers inland from the transgressive limit of the contemporary marine shoreline and, therefore, within the inland limit of relative sea-level control on fluvial sedimentation. The Qc Unit was deposited during a time of large Milankovitch-scale sea-level fluctuations that were triggered by alternate glacial and interglacial periods. The resulting sea-level curve, as recorded by global δ18O variations (e.g., Imbrie et al., 1984, Bassinot et al., 1994, Lisiecki and Raymo, 2005), was characterized by short periods of sea-level highstand, averaging 10–15 ka, and a distinct asymmetry, reflecting high rates of sea-level rise (in the order of 10–15 m/ka) and low rates of sea-level fall (1–1.5 m/ka). In this frame, as the rates of eustatic sea-level changes were sufficiently high to overshadow the effect of the regional tectonic uplift recorded in the study area, glacioeustasy appears to have exerted the principal control on trend of relative sea-level oscillations and accommodation space in the A/S ratio. Moreover, changes in sediment supply to fluvial systems were controlled by the alternating glacial and interglacial periods that influenced the vegetation cover on the slopes and their erosion. This situation led to the formation of LASTs soon after the end of the full glacial conditions, when rates of sediment supply were high and values of sea-level rise were low, and the development of HASTs during post-glacial sea-level rise, when rates of accommodation space exceeded sediment accumulation rates. Long-lasting soil forming conditions, which led to development of the mature QcS2 and QcS3 paleosols, prevailed during fully interglacial periods and, therefore, reflect allogenic changes.

Given the basin-marginal context and evidence for an uplift regime throughout accumulation of the Qc Unit, the observed superposition of two distinct sequences in such a low-accommodation setting can be attributed only to the creation of additional accommodation space for fluvial sediments by exceptionally high-amplitude sea-level rises. Estimate of sea levels during the major interglacial stages between MIS 16 and MIS 8 reveals that the MIS 12 and 11 and MIS 10 and 9 deglacial transitions were characterized by unusually high amplitude sea-level rises and that during peak interglacial times (i.e., during MIS 11 and MIS 9) sea-level was close to, or higher than, its present position (e.g., Siddall et al., 2007 and reference therein; Olson and Hearty, 2009, Rohling et al., 2010, Raymo and Mitrovica, 2012). In particular, the sea-level rise at the MIS 12 to MIS 11 glacial–interglacial transition was suggested to be the largest (about 160 m) in the last million years (Hearty et al., 1999). Blain et al. (2012) reconstructed the differences between the present mean temperatures (annual, warmest month, and coldest month) and their equivalents during MIS 11 and MIS 9.3 and concluded that both stages were warmer than the present. Conversely, interglacial stages prior to that time were substantially cooler, and exhibited lower sea levels (e.g., Jouzel et al., 2007). In the Mediterranean area, deposits that are correlated with MIS 11 and MIS 9 are rare and poorly documented. However, a recent study on the living conditions (both water temperature and salinity) of stromatolites occurring within two middle Pleistocene terraced deposits exposed along the southern Adriatic coast (about 260 km south-east of the study area), indicates that tropical/subtropical conditions were present in the area during MIS 11 and MIS 9 (De Santis et al., 2014). Based on these considerations, deposition of Qc1 and Qc2 sequences can be tentatively correlated with the glacial/interglacial transitions from late MIS 12 to full MIS 11 and from late MIS 10 to full MIS 9, respectively. Accordingly, it follows that: (i) the SU1 unit-bounding unconformity is older than MIS 12; ii) QcS2 corresponds to the MIS 11 interglacial; iii) the SU2 unconformity can be referred to the MIS 11–10 sea-level falling to lowstand erosion; (iv) QcS3 starts to develop during the MIS 9 interglacial; and v) SU3 is a compound sequence boundary that encompasses the post-MIS 9 valley deepening and alluvial terraces deposition.

Conclusions

Nonmarine strata of the middle Pleistocene Qc Unit were deposited in an uplifting, low-accommodation setting by gravelly braided rivers that originated from the central Apennines to the west. The Qc Unit is characterized by fluvial sediments throughout its depositional history; however, its stratigraphic arrangement has changed systematically due to changes in the A/S ratio. A high-resolution sequence stratigraphic framework has been adopted to interpret the history of the Qc Unit in response to glacio-eustatic changes in sea level, and to subdivide the continental stratigraphic record into two nonmarine depositional sequences bracketed by prominent subaerial unconformities. Each sequence includes a relatively conformable, fining-upward succession of strata characterized by conglomerate-dominated, multi-storey, multi-lateral stacking of fluvial channels at the base (low-accommodation systems tract, A/S ratio smaller than unity) overlain by a dominantly fine-grained floodplain succession (high-accommodation systems tract, A/S ratio larger than unity) locally weathered by shortly living soil formation episodes. However, the fine-grained succession is also weathered on top by a reddish, leached and strongly weathered mature paleosol (zero to negative A/S ratio).

Because rates of glacioeustatic sea-level changes during middle Pleistocene time were considerably higher than rates of contemporary regional uplift in the Peri-Adriatic basin, tectonic disturbance in the depositional areas did not obscure the eustatic signal. As a consequence, high-amplitude eustatic sea-level changes and the resulting shifts in shoreline position are believed to have been the dominant control on the cyclic depositional character of the succession. To constrain the climatic signal for paleosol formation, the two sequence-capping mature paleosols have been investigated. The results of these studies suggest that they were developed under humid and warm climatic conditions associated with interglacial phases, which have been correlatively attributed to MIS 11 and MIS 9.

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Table 1. Summary of the most distinctive sedimentologic attributes of sedimentary facies identified in the Qc Unit.

Facies association	**Facies code**	**Description**	**Interpretation**
FA-A	Gh	These are the most abundant deposits in FA-A and are composed of ungraded, clast-supported conglomerates containing a poorly sorted matrix of fine- and coarse-grained sands. In general, clasts are granule to cobble in size, moderately to poorly sorted, and typically rounded to well-rounded. Due to lack of vertical variations of sediment grain size, this facies typically displays little or no apparent bedding other than crude horizontal stratification. However, where discrimination of individual sedimentation unit is possible, bedding planes are planar to highly irregular. Individual beds are lenticular, 0.3–2.5 m thick and up to 10 m wide, with sharp top and basal contacts. Broad and shallow erosion surfaces, marked by the alignment of outsized, angular to subangular sandstone or mudstone blocks measuring up to 80 cm in diameter, have been observed locally. Wherever there is a predominance of discoidal clasts, a crude, patchily developed *a*(t)*b*(i) imbrication is	The characteristics of massive or crudely-stratified, clast-supported conglomerates of facies *Gh* strongly support an active bed-load transport with clasts that only moved during larger flood events and suggest deposition as gravel sheets or low-relief longitudinal bars within shallow braided channels (e.g., Smith, 1974, Hein and Walker, 1977, Rust, 1978). Vertical accretion of longitudinal gravel bars occurs during the high *flood* stages and ceases during low-water stages, when the elevated parts of these bedforms become emergent. Sandstone or mudstone blocks may represent portions of bank material broken from the channel margin.

Facies association	Facies code	Description	Interpretation
		observed. Paleocurrent directions from clast imbrication indicate north-westward sediment transport.	
	Gp	This facies consists of lenticular units of planar cross-stratified conglomerates that are up to 2 m thick and less than 15 m wide and bounded by flat surfaces at the top and planar to concave-upward surfaces at the base. It occurs as wedge-shaped individual sets of inclined beds that dip from 15° to 20° toward the basal surface. These gravelly foresets are well defined by remarkable variations in textural features (matrix content and alternations in grain size) and consist of a few centimeter to decimeter thick layers that become finer grained obliquely upward. Most of the component clasts tend to lie with the *ab* planes parallel to the plane of the foresets, resulting in a clast imbrication that dips in the same direction as the host cross-bedding (pseudo-imbrication). Paleocurrent directions determined from the foreset orientations of this facies are similar to those obtained from gravel imbrication of horizontally stratified conglomerates of facies *Gh*.	Sets of cross-stratified clast-supported conglomerates have been widely interpreted to record the downstream migration of large, isolated, mid-channel transverse bars (Hein and Walker, 1977; Massari, 1983; Steel and Thompson, 1983; Rust, 1984; Yagishita, 1997). In this frame, the high-angle foresets are the result of avalanching slip faces at the leading edge of the gravel bar, typically during falling-water stages.
	Gt	This is the least abundant facies in the studied FA-A. It consists of cross-bedded conglomerates filling isolated troughs with concave-upward and erosional lower bounding surfaces. Individual sets of trough cross-bedded conglomerates are up to 2.5 m thick and, generally, only continuous for a few tens of meters due to truncation by other sediment packages. Foresets are concave-up and generally conformable with the inclined erosion	Trough cross-bedded conglomerates may originate due to dissimilar processes within gravel-bed braided rivers and are commonly interpreted to represent active channel-fill deposits and/or three-dimensional gravel dunes and/or scours or pools (e.g., Siegenthaler and Huggenberger, 1993; Khadkikar, 1999). Based on the attitude of the lower bounding surface and internal characteristics, in the present case facies *Gt* can be

Facies association	Facies code	Description	Interpretation
		surface, vary in thickness from 0.3 m to 0.8 m, and are clast-supported, with pebbles sitting in a medium- to coarse-grained, sub-angular to sub-rounded, poorly sorted sandstone matrix. Paleocurrent orientations are generally slightly oblique to the mean direction determined from clast imbrication in the interbedded facies *Gh*.	interpreted as having being deposited as the infill of minor channels. The oblique orientation of the paleocurrent directions from the trough cross-sets relative to those from gravel imbrication in the adjacent facies *Gh* suggests that facies *Gt* probably represents small-scale channels that obliquely dissected the main longitudinal bar during a falling-water stage (Yagishita, 1997).
FA-B	Fl	This facies is composed of thinly interbedded siltstone and very fine-grained sandstone. Individual beds are lenticular or irregularly wedge-shaped, laterally persistent for tens of meters.	Facies *Fl*, reflecting deposition from suspension and weak traction currents, is interpreted to record overbank deposition on a floodplain and is likely to represent levee and/or crevasse-splay deposits.
	Fm	It consists of light grey, massive, moderately to poorly sorted siltstones, centimetre- to decimetre-thick muddy siltstones and mudstones that lack any observable sedimentary structures and also includes bioturbated layers and freshwater gastropods. Laterally discontinuous, centimeter- to decimeter-thick, weakly developed paleosols are present at distinct stratigraphic levels. The paleosols show evidence of carbonate migration and precipitation (small concretions and nodules) but not of carbonate leaching, clay illuviation or other important changes in structure and colors.	The fine-grained texture of facies *Fm* suggests that its deposition took place mainly from suspension fall-out under low energy conditions and that it may represent overbank deposition in floodplain areas. The presence of weakly-developed paleosols and a freshwater molluscan fauna all support the interpretation of subaerial exposure during sedimentation linked to autigenic changes of the sedimentary environments.

Table 2. Summary of the most distinctive macroscopic pedogenic features within the paleosol profiles of the Qc Unit.

Pal-eosol profile	Soil horizon	Depth (cm)	Description
QcS1	Btk	0–50	Medium to coarse, moderate subangular blocky structure; moist 10YR 6/6 brownish yellow; loamy sand; < 2% fine to coarse flinty and calcareous fine gravels, angular to subangular; 10% fine to coarse $CaCO_3$ concretions and nodules; 2% fine black Fe/Mn masses; violently effervescent; gradual lower boundary
	Bk	50–60	Massive; moist 10YR 7/4 very pale brown, loam; 2% fine to very coarse angular to subrounded flinty and calcareous gravels; 20% fine to coarse $CaCO_3$ concretions and nodules; violently effervescent; gradual lower boundary
	Ck	60–100	Massive; moist 2.5YR 8/6 yellow laminated alluvial silts and sands; 40% $CaCO_3$ soft masses, concretions and nodules; lower boundary not reached
QcS2	Bt1	0–40	Medium to coarse, strong subangular blocky structure; moist 5YR 5/8 yellowish red; clay loam; 2% fine to coarse flinty gravels, angular to subangular; 2% fine to medium clay coatings on the aggregates; 5% fine black Fe/Mn masses; noneffervescent; clear wavy lower boundary
	Bt2	40–75	Medium to fine, moderate subangular blocky structure; moist 5YR 6/8 reddish yellow, sandy loam to sandy clay; 2% fine to very coarse angular to subrounded strongly weathered flinty gravels; 2% fine to medium clay coatings on the aggregates; 5% fine to large black Fe/Mn masses; 5% whitish carbonate masses; groundmass noneffervescent; clear wavy lower boundary
	Ck1	75–100	Medium to strongly cemented rounded to subrounded unsorted calcareous and flinty gravels with sandy matrix; structureless; white; the clasts closer to the upper boundary with the overlying Bt2 horizon, are strongly weathered; violently effervescent; clear abrupt lower boundary
	Ck2	100–200	Massive, structureless sandy loam; white; violently effervescent
QcS3	Btgk	0–55	Medium to coarse, strong subangular blocky structure; moist 5YR 5/3 reddish brown; clay loam; 20% fine to coarse strongly weathered flinty gravels, angular to subangular; 10% fine to medium clay coatings on the aggregates; 5% fine black Fe/Mn masses; 5% irregular redox depletion features; 20% coarse to very coarse $CaCO_3$ nodules and concretions; groundmass noneffervescent; clear wavy lower boundary
	Btk1	55–130	Medium to fine, strong subangular blocky structure; moist 2.5YR 4/6 red, clay loam; 20% fine to very coarse angular to subrounded strongly weathered flinty gravels; 15% fine to medium clay coatings on the aggregates; 5% fine to large black Fe/Mn masses; 20% coarse to very coarse $CaCO_3$ nodules and concretions; groundmass noneffervescent; clear wavy lower boundary
	Btk2	130–155	Medium to fine, strong subangular blocky structure; 5YR 4/4 reddish brown; 30% fine to very coarse angular to subrounded strongly weathered flinty gravels; 10% fine to medium clay coatings on the aggregates 5% fine black Fe/Mn masses; 20% fine to very coarse $CaCO_3$ nodules and concretions; clear wavy lower boundary

Pal-eosol profile	**Soil horizon**	**Depth (cm)**	**Description**
	Bkm	155–175	Moderately to strongly indurated, finely laminated to massive illuviated calcium carbonate; 2.5YR 8/1 white to 2.5YR 8/4 pink, violently effervescent; laterally pockets of fine to medium strong subangular blocky structure, 2.5YR 5/3 reddish brown, clay loam, violently effervescent
	Ck	175–275	Massive, structureless, weakly preserved sedimentary structures, sandy loam; 2.5YR 7/3 pale yellow; violently effervescent; lower boundary not reached

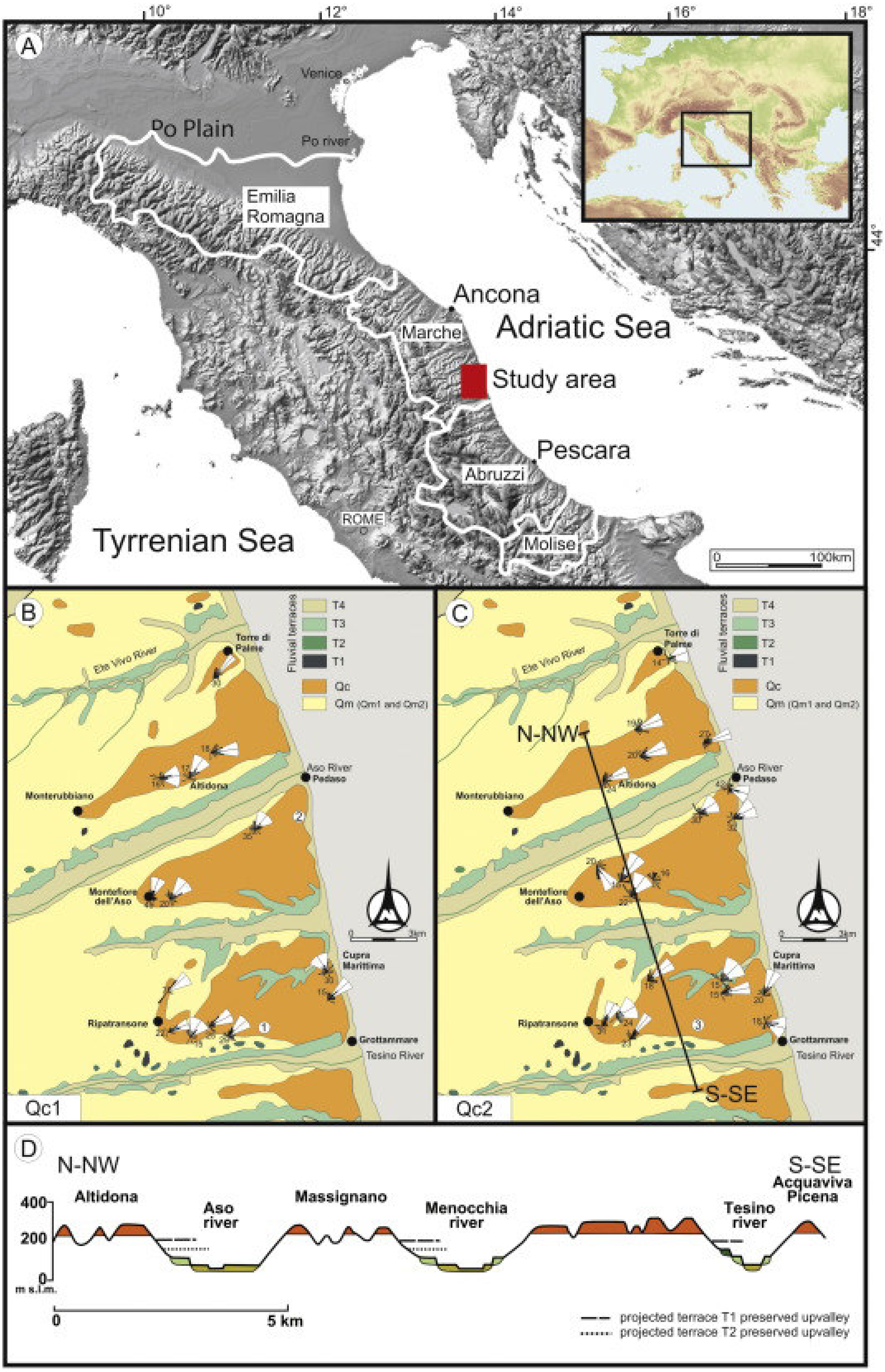


Figure 1. A) Map of central Italy showing the location of the study area (red rectangle) in A and B. B) Paleocurrent distribution for Qc1. Encircled numbers indicate position of the studied paleosols (1 = QcS1; 2 = QcS2. C) Paleocurrent distribution for Qc2 (B); 3 = QcS3. D) NNW–SSE-oriented simplified cross-section showing the relationships between the Qc deposits on the watersheds and the four alluvial terraces within the river valleys.

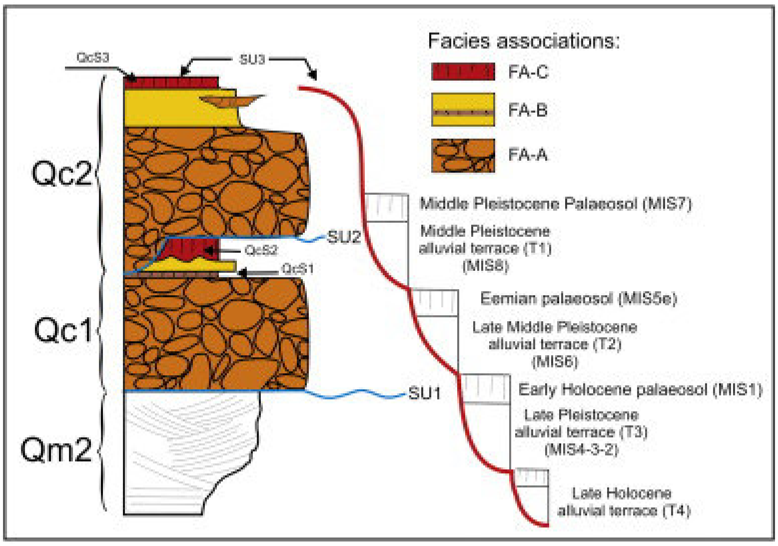


Figure 2. Cartoon-style summary of the stratigraphic relationships between Qm2 Unit, Qc Unit and the four fluvial terraces.

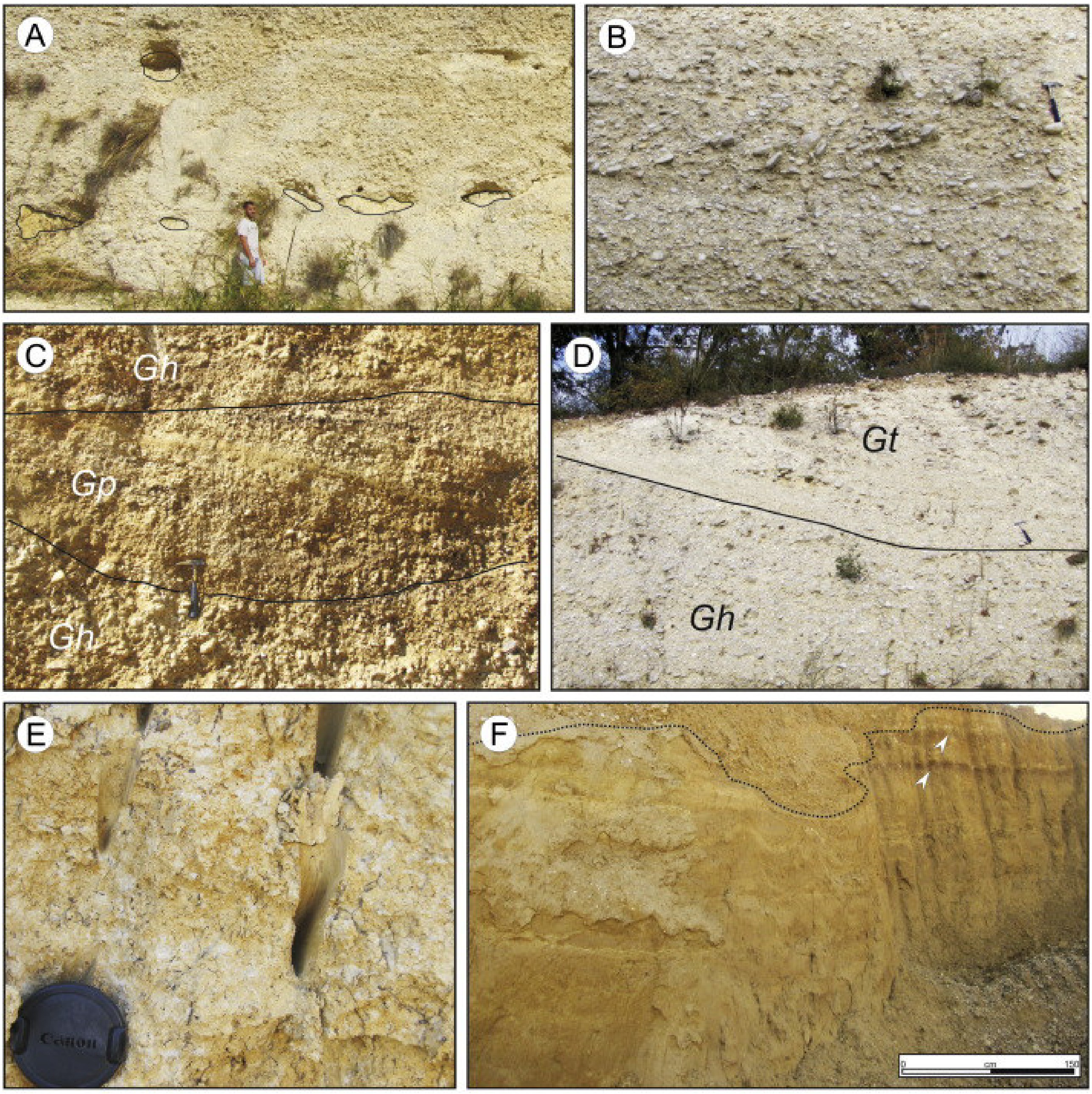


Figure 3. Compilation of field photographs showing the main sedimentological characteristics of facies associations observed in the Qc Unit. A 30 cm long rock hammer and a 6.5 cm in diameter lens cap are used for scale. A)

Amalgamation surface marked by large chunks of mudstone. Photo is from Torre di Palme. B) Outcrop wall, about 4 m high, showing clast-supported, massive or crudely bedded conglomerates (facies Gh). Note the crude stratification and pronounced imbrication of clasts (paleocurrent from left to right). C) Detail of an individual set of planar cross-stratified conglomerates (facies Gp) resulting from alternations of small pebbles and gravelly sands and showing a flat top and a planar to concave-upward base. Cross stratification developed by a downstream migration of an avalanching front. Dip direction of the foresets indicates paleoflow toward the north-east (to the right). D) Trough cross-bedded conglomerates (facies Gt) draping the margin of a minor channel incised in facies Gh. E) Close view of massive, organic-rich mudstones (facies Fm). Note the occurrence of root traces, scattered carbonaceous fragments, and intense mottling. F) Panoramic view of the same sediments. White-headed arrows on the upper right-hand side point to poorly developed paleosols.

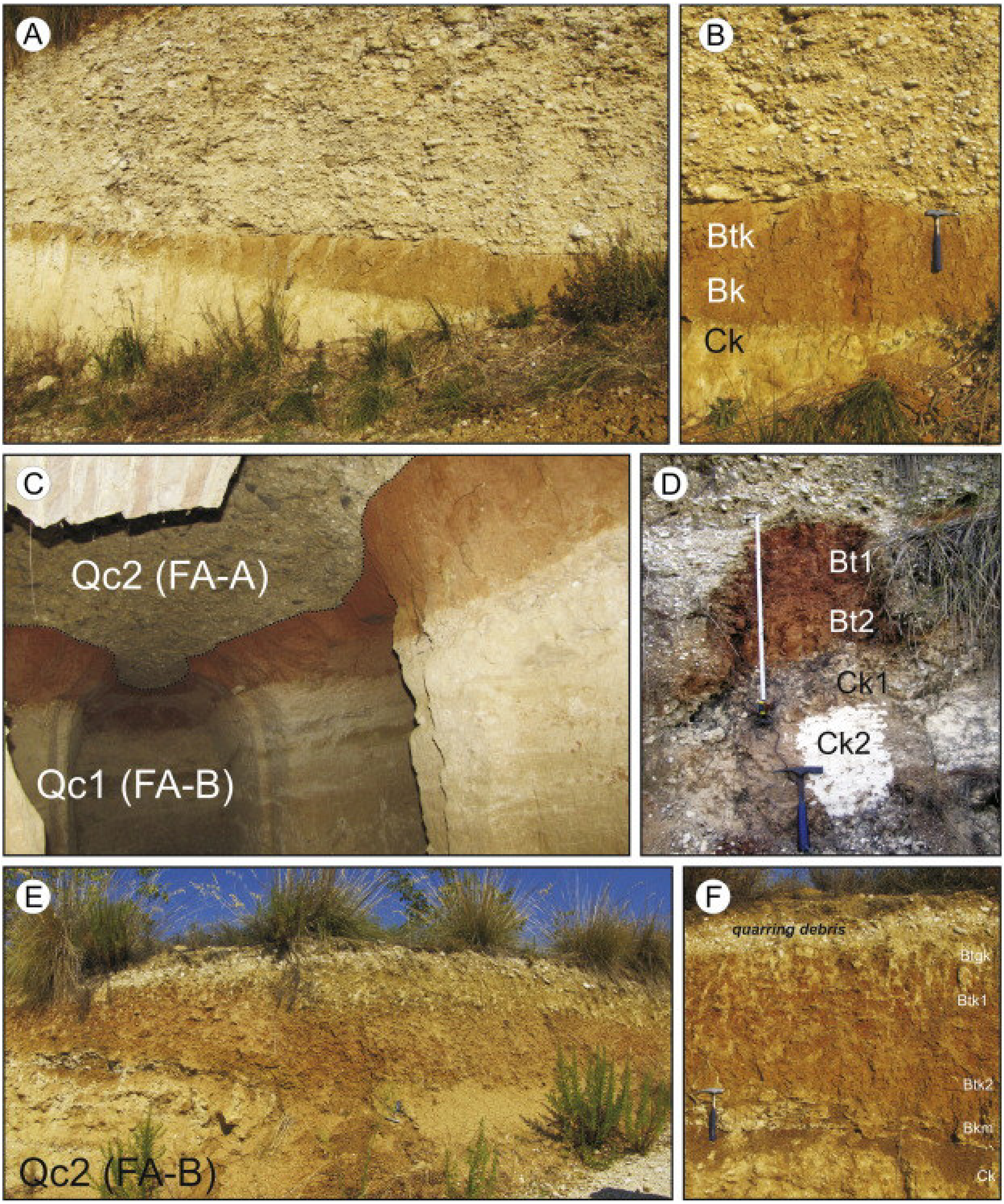
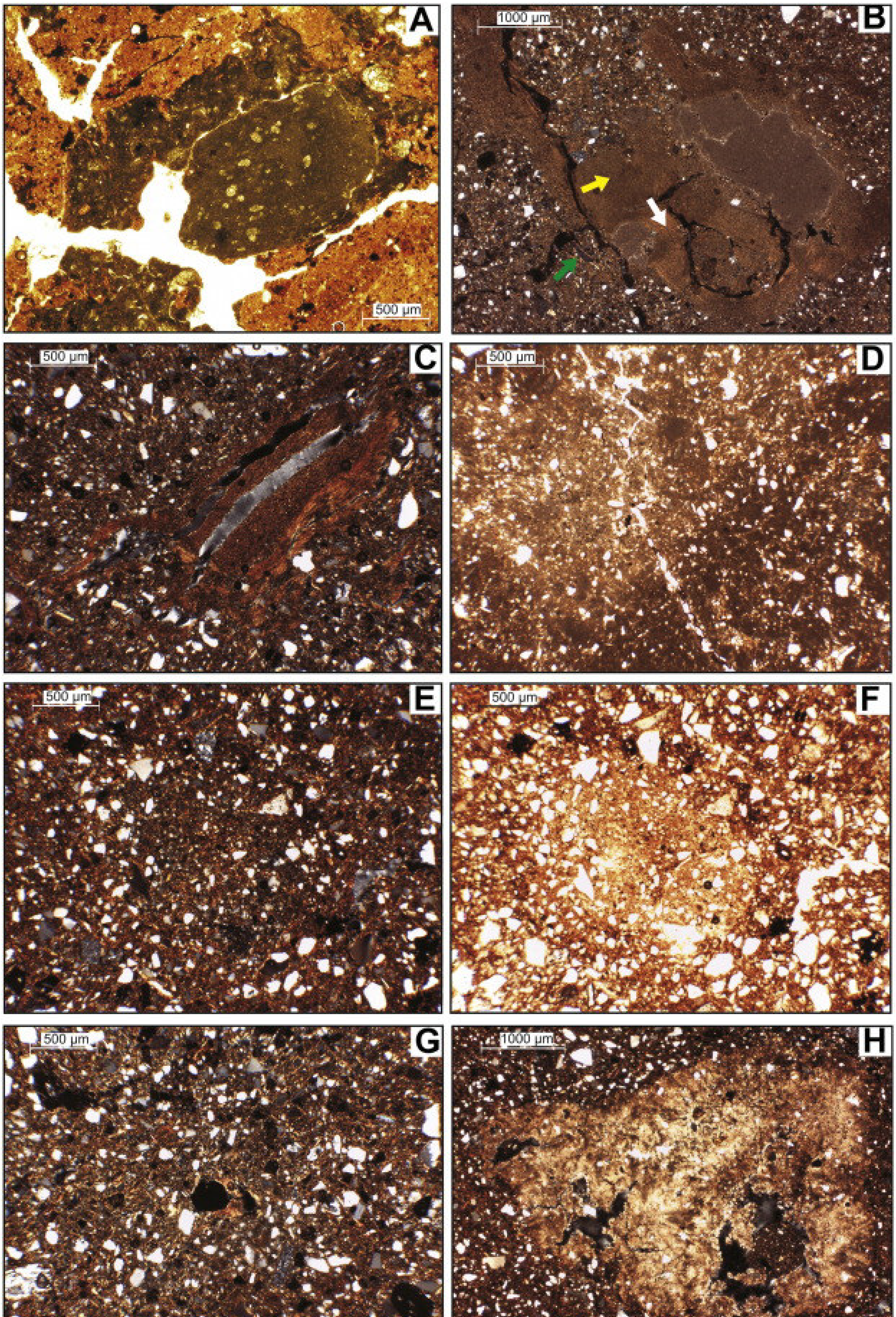


Figure 4. A) Paleosol QcS1 (43°00′47.29″N–13°50′43.31″E). The limited thickness and lateral continuity indicate the importance of the erosional processes before the deposition of Qc2. B) The QcS1 paleosol shows moderate weathering of the primary minerals and incomplete leaching of primary carbonates although little clay illuviation led

to the formation of a weakly expressed Bt horizon. Carbonate precipitation affected the whole profile. C) The QcS2 paleosol near Pedaso (43°05’33.53”N–13°50’37.19”E). At this site, the paleosol profile is severely truncated by the basal erosional surface of Qc2 within a pre-Roman Piceni Grave. D) The rubified Bt horizons of the QcS2 paleosol overlay deep Ck horizons formed on silty sands and gravelly lenses. E) The relict QcS3 paleosol developed on top of Qc2 corresponding to the present-day topographic surface (43°00’41.89”N–13°50’43.42”E). Its preservation is irregular and depends upon the erosional processes that acted at the surface. F) The soil profile of the QcS3 paleosol is the result of polycyclic and polygenetic processes and is characterized by thick deep Bt horizons on top of indurated calcic C horizons.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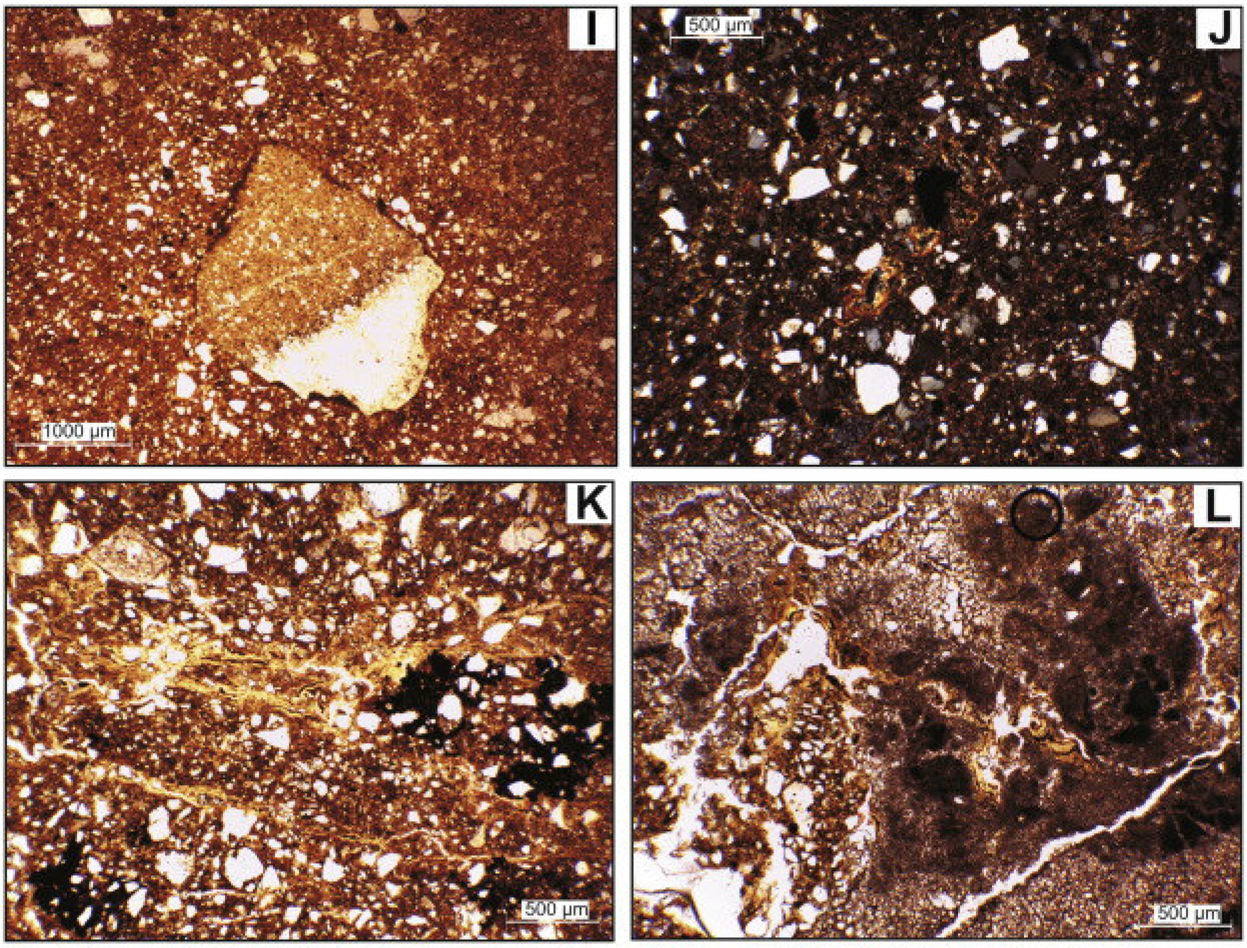

Figure 5. Micromorphological features of QcS1, QcS2 and QcS3 paleosols. A) QcS1, PPL, Btk. Unleached primary carbonate sand grain. Note the poorly mobilized calcium carbonate around the grain including preserved foraminifera individuals. Fe/Mn nodules and impregnation features are also common. B) QcS1, XPL, Btk. Evidence of multiple generation of carbonate coatings and infillings due to illuviation of micrite mixed with clays (white arrow) also around CaCO3 nodules followed by massive micritic infillings (yellow arrow). The groundmass also shows very small clay grano-coatings and weak strial b-fabric (green arrow) possibly due to shrinking and swelling processes. C) QcS1, XPL, Btk. The two phases of carbonate precipitation, the older coating characterized by orange colours and fine weak lamination with presence of clays and the younger micritic and detrital silty illuviation features. D) QcS1, PPL, Bk. General aspect of the opaque groundmass characterized by strong micritc impregnation. E) QcS2, XPL, Bt1. General aspect, the silty-sandy coarse fraction is made exclusively of quartz grains and weathered flint fragments. Small clay coatings and infillings incorporated within the groundmass are also common. Weakly developed strial b-fabric is also evident. F) QcS2, PPL, Bt1. Hydromorphic features made of Fe/Mn nodules and impregnated/depleted areas. G) QcS2, XPL, Bt1. Reddish-orange microlaminated clay coatings around voids and grains with typical extinction bands. Smaller clay illuviation features are strongly incorporated within the groundmass. H) QcS2, XPL, Bt2. Orthic calcitic nodule with distinct boundary destructing the groundmass and incorporating few quartz grains. I) QcS3, PPL, Btk1. Strongly weathered flint fragments with Fe/Mn staining and coatings. J) QcS3, XPL, Btk1. The older, dark reddish, microlaminated, fragmented and partially incorporated clay coatings. K) QcS3, PPL, Btgk. Horizontal planar voids with the younger generation of more limpid clay infillings alternated with thin black Fe/Mn oxides. Large black anorthic Fe/Mn nodules are also common. L) QcS3, PPL, Btk2. Two main generations of carbonate precipitation. The darker micritic phase followed by the growth of limpid sparitic crystals. The younger and more limpid generation of clay coatings partially fragmented is deposited after the CaCO3 precipitation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

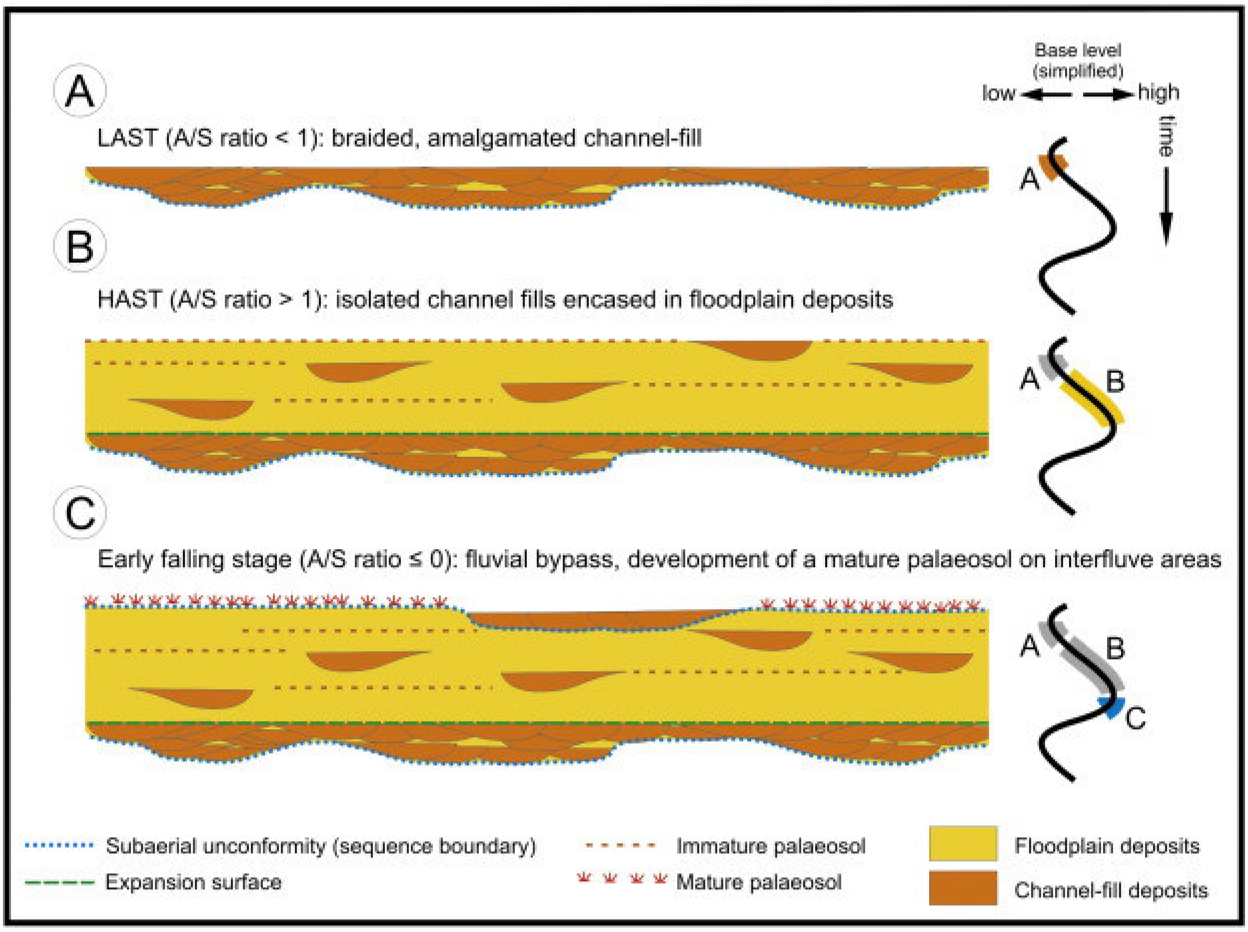

Figure 6. Series of schematic diagrams illustrating systems tract development in the Qc Unit sequences related to the base-level cycle (accommodation) and changes in sediment supply. A) The LAST was deposited during the early stages of deglaciation, when the increase in accommodation space generated by eustatic sea-level rise was partially masked by the regional tectonic uplift whereas high rates of sediment supply were favoured by a relatively poor vegetation cover (A/S ratio < 1). During this early stage of base-level rise, streams migrated mostly laterally, stacking coarse-grained sheets one upon another and resulting in minor aggradation. The succeeding balance between accommodation and sediment supply (A/S ratio = 1) resulted in a systems tract bounding expansion surface. B) The HAST formed during the post-glacial period, when eustatic sea level rise was much faster than tectonic uplift and sediment supply was reduced by the increase in vegetation cover (A/S ratio > 1). A continued increase in rates of base-level rise resulted in very rapid creation of accommodation space and aggradation. Channels were no longer able to rework their entire floodplains and the amount of preserved overbank sediments greatly increased, producing isolated channel conglomerate bodies encased in mud-rich sediments with weakly developed soils. C) The HAST ceased to form during the peak of the interglacial sea level high stand, when the rate of tectonic uplift has first equalled and then exceeded the rate of eustatic sea-level rise, leading to a net relative sea-level fall. During this phase of fully interglacial conditions the accommodation space was zero or negative (and so was the A/S ratio) and the fluvial system was characterized by stream entrenchment and sediment bypass, producing an irregular regional unconformity, and development of mature interglacial paleosols in interfluve areas.

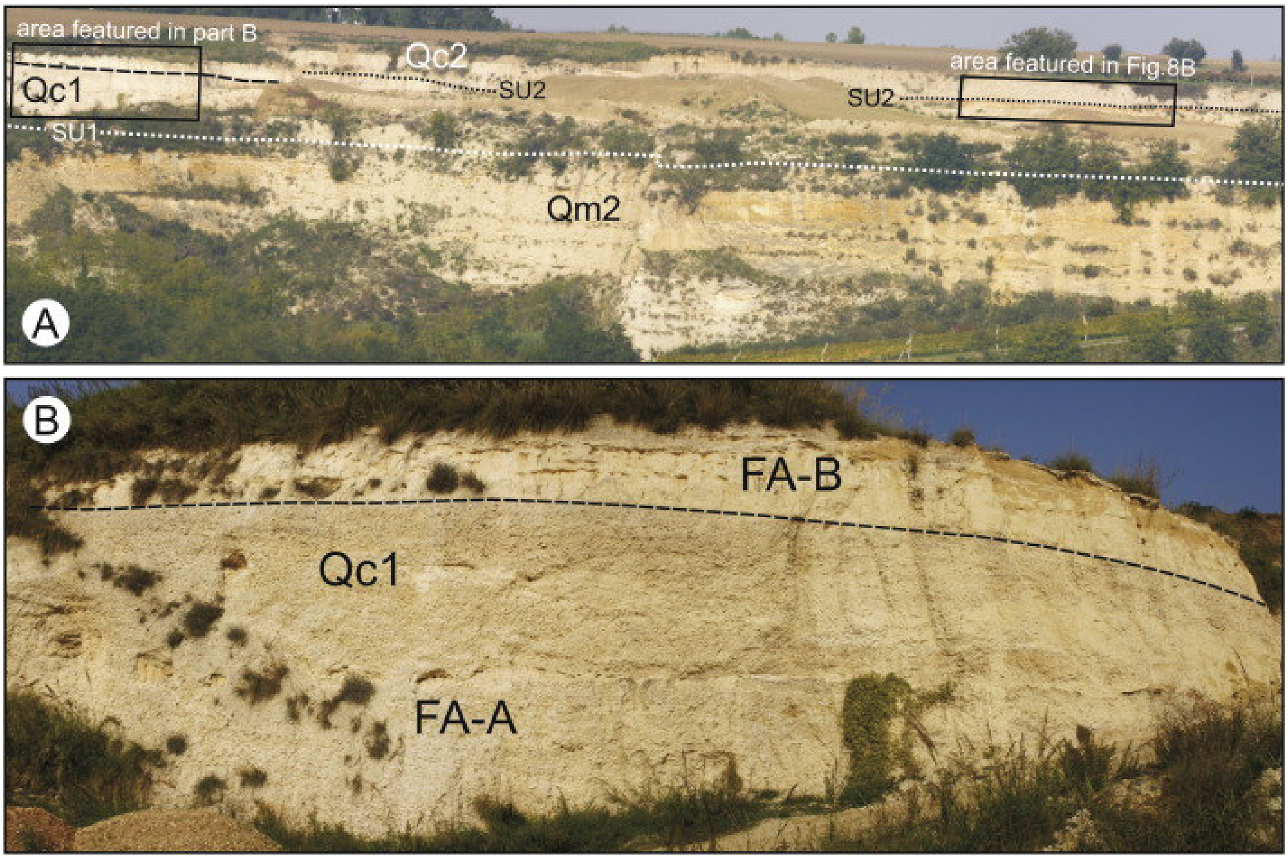

Figure 7. Photos of the expansion surface in sequence Qc1 exposed in a gravel quarry near Torre di Palme. A) Panoramic view the dashed black line demarcates the expansion surface, whereas the dotted lines underscore the sequence boundaries (SU1 and SU2). B) Enlargement of the expansion surface within the boxed area in A. Superposition of floodplain sediments over braided fluvial conglomerates across the surface indicates a transition from a deposition in a low-accommodation regime to a high-accommodation one.

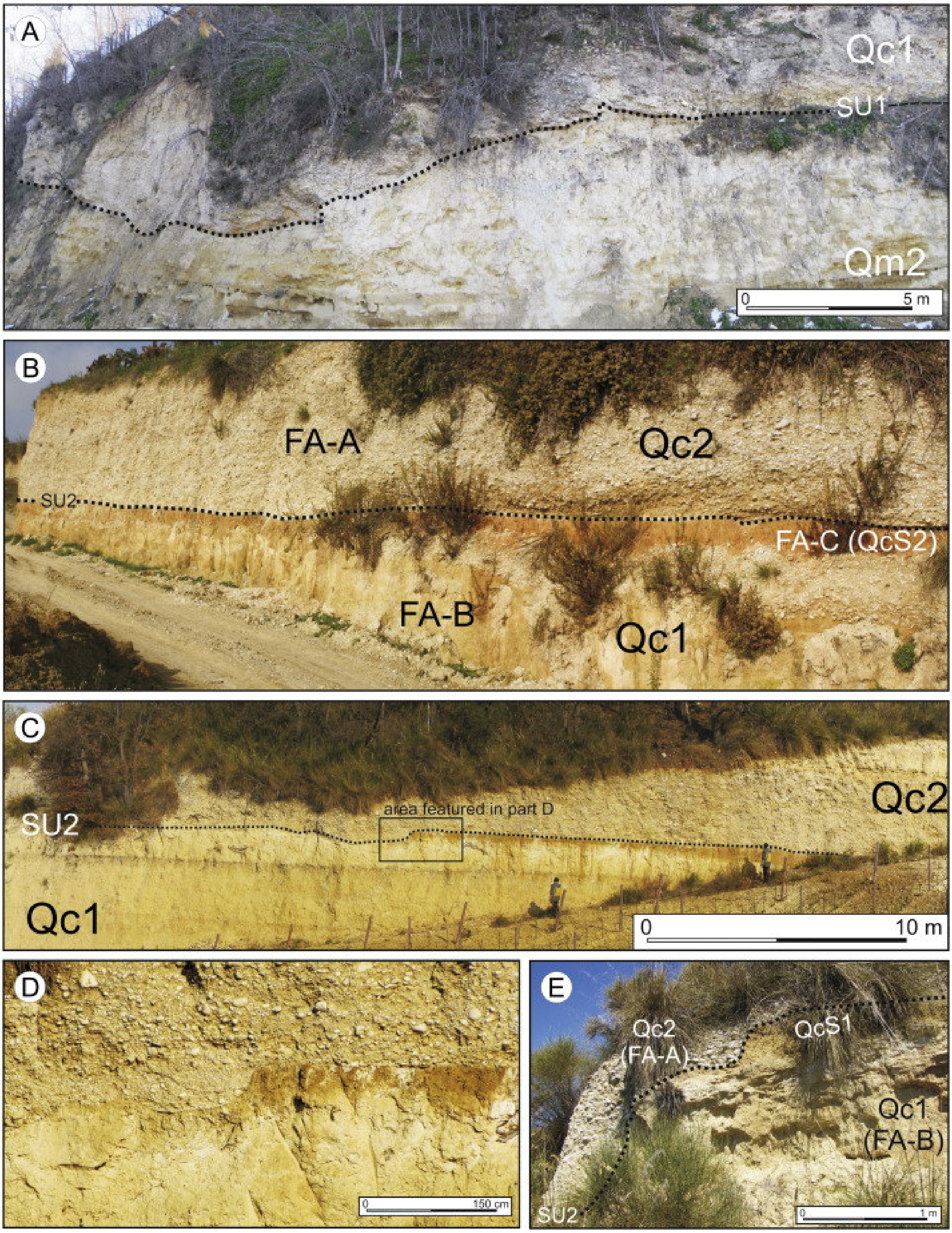

Figure 8. A) The base of sequence Qc1 is a sharp and strongly erosional unconformity (SU1). This surface records regional bevelling of the Qm2 Unit produced by a significant reduction of the ratio between accommodation and sediment supply. B) Photo of the SU2 surface in a gravel quarry near Torre di Palme (43°08’06.13”N–13°48’28.62”E). C) Panoramic picture showing a break in the lateral continuity of the QcS1 paleosol due to truncation by a low-angle erosion surface (SU2) at the base of Qc1. D) Enlargement of the area of the inset box in C. E) Detail of a steep-walled incisions cutting a few meters through the underlying floodplain deposits.

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